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Distributed Energy Resources based Microgrid: Review of Architecture, Control, and Reliability

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***Abstract*—To accomplish feasible large-scale integration of distributed energy resources (DER) into the existing grid system, microgrid implementation has proven to be the most effective. This paper reviews the vital aspects of DER based microgrid and presents simulations to investigate the impacts of DER sources, electric vehicles (EV), and energy storage system (ESS) on practicable architectures' resilient operation. The focus is primarily on the concept and definition of microgrid, comparison of control strategies (primary, secondary and tertiary strategies), energy management strategies, power quality issues associated with DER based microgrid, and state-of-the-art entities such as ESS and EV's applications towards microgrid reliability. Following discussion on the different attributes of DER sources-based microgrid, simulations are performed to verify the results of the past works on the effects of solar, wind energy sources, ESS, and EVs on the microgrid frequency response. Additional simulations are conducted to assess the influences of DERs, ESS, EVs and their operational strategies on the microgrid reliability aspects.**

***Index Terms*—Distributed Energy Resources (DER), Electric Vehicle (EV), Energy Storage System (ESS), Frequency response, Microgrid, Power Quality, Reliability**

I. INTRODUCTION

Electrical energy is one of the most indispensable components of the modern world. However, the process of electrical energy production from fuel energy sources has caused a great deal of increase in global emission level. Moreover, pollution in the environment due to the consumption and diminution of conventional energy sources is resulting in environmental pollution while the energy demand is ever-increasing [1]. Non-conventional energy sources solve many issues complimenting the use of fossil fuel sources while applicable technologies associated with renewable energy sources such as sun, wind, tidal are becoming more economically feasible with time [2].

A microgrid is a concept that accommodates renewable and conventional sources on a small (or 'micro') scale, while merging the integral parts of the power system to attain reliable operation throughout the generation to load demand. Microgrids are distributed heterogeneously in an interconnected or isolated mode while including energy sources and distributed storage management such as monitoring, control, and automation [3]. The conducive architecture of distributed energy resources (DER) (such as microgrid), located near the load, almost eliminate transmission losses. From a grid point of view, the main advantage of a microgrid is that it is treated as a controlled entity within the power system which can operate as a single load [4]. The advantage of microgrids in remote region electrification makes it viable over expensive grid integration, which in many cases is not possible due to environmental or natural build-up. These advantages have promoted the deployment of microgrids worldwide. The United States has been the historical leader in deployed microgrid capacity. In 2018, the U.S. and Asia had roughly the same capacity of operating, under development, and proposed microgrids, each with 42% of the market [5]. Despite these advantages, microgrids require careful planning and consideration in the financial, technical, economic, and regulatory areas for their efficiency [6].

This paper aims to provide a review of various state-of-the-art features of the DER based microgrid that contribute towards the implementation and reliable operation of clean energy sources based futuristic power system. In this paper, a simulation-supported review of recent works in the areas of control architectures, energy management, power quality, and reliability are presented. Additionally, the impacts of energy storage systems (ESS) and electric vehicles (EV's) on the abovementioned areas of the microgrid are investigated.

The discussion on architecture and control of the DER based microgrid system based on reliable operation and management is segmented as follows:

1) Comparative review study among different control schemes applied into DER based microgrid topology,
2) Energy management and power quality means within the microgrid in terms of optimization and stable operations,
3) Efficient integration and integral impacts of the EVs as well as ESS into the reliable operation of microgrid and lastly,
4) Simulations to verify existing literature's results regarding the frequency regulation control schemes and microgrid reliability in the presence of DER and EVs.

The structure of the paper is as follows. Section II reviews the range of control challenges DER based microgrid system encounters and the control methodologies investigated in conducted research to overcome such challenges. Sections III highlights current research outcomes on energy management strategies and power quality enhancement techniques in DER based microgrid systems. Section IV provides comprehensive summaries of the participation of EVs and ESS in the microgrid. Section V presents a review on the reliability assessment of microgrids in presence of DERs, ESS, and EVs. Section VI presents frequency response results of the microgrid in the presence of DERs, ESS, and EVs with their respective control strategies. The reliability analysis of DER-based microgrid under the influence of ESS and EVs is presented in section VII. The paper is concluded in section VIII.

II. CONTROL SCHEMES OF DISTRIBUTED ENERGY SOURCES-BASED MICROGRID

Microgrid interfaces DERs and storage components through power electronic converters. Control strategies applied to the converters play a crucial role in the performance of microgrids. Some of the key challenges for power electronic converter interfaces in a microgrid are summarized below [7]:

1) They should be able to maintain minimally distorted sinusoidal voltage output along with controllable phase angle and amplitude.
2) They should account for non-linear characteristics of loads the microgrid will serve.
3) They should limit the output current to protect the distributed source switches from external faults.
4) They should account for frequency and voltage stability problems that could be exacerbated for islanded microgrids due to their structural weakness.

Voltage regulation based control of electronics converter such as sliding mode control has been quite effective regarding variation in load or generation. Real and reactive power sharing among distributed renewable sources and electric grid takes place efficiently under consideration of better voltage controllability and swift switching response in sliding mode control strategy [8]. In response to the drawbacks of the traditional control strategies, [9] proposed an adaptive backstepping sliding mode control strategy for better dynamic regulation performance. [10] has proposed a second-order sliding mode control for the power flow control of a hybrid ESS that yields improved results compared to the classic PI control scheme. An adaptive version of the sliding mode control based on an Ad-hoc chattering-free algorithm is proposed in [11] that provides robust frequency and voltage restoration in islanded microgrids. The proposed control strategies based on sliding mode provide reliable control of terminal voltage and frequency of DERs and ensures protection to the power electronic converters from external faults.

Due to the variability associated with the generation of distributed sources, fixed speed distributed generation (DG) using a synchronous machine remains the principal energy source in isolated and remote areas. To address this issue and provide maximum utilization of renewable sources, [12] has proposed optimum configurations for variable speed generators (VSG). Another problem lies in the variability introduced by unbalanced sources/loads. To provide a balanced output voltage in case of such unbalanced source/loads, such as photovoltaic source or single-phase load within DER based microgrid, grid forming inverters suffer from certain functional issues. To address such lack of control-related system instability, the vector control strategy of three-leg grid-forming inverter based on d-q axis for delta-wye orientated transformer operating in a hybrid stand-alone power system is examined [13].

A. Hierarchical Control Strategies in a DER based Microgrid

The different levels of control schemes applied within microgrids are of three kinds on a hierarchy basis [14]. The control strategies are described in detail as follows:

1) Primary Control Strategy: The primary control scheme is devoted to maintaining voltage and current control via control of the converters that link with the distributed resources and storage devices. The primary control also includes maximum power extraction, sharing of power among other devices and architectures. The objectives of the primary control level happen to be managing the value and frequency of the voltage, passing on the inputs for inner voltage and current loops, and circulating current limitation [15].

Droop control is a familiar primary control structure that is based on the decoupling of real and reactive power on the transmission circuit due to line reactance. Voltage droop control (VDC) increases the DER based microgrid's reliability by ensuring that each source delivers an output power according to the amount determined by the connected power electronic converter. Initial works in VDC focused on the mismatch in the output impedances of the closed-loop voltage controller of the DG units [16], [17]. An adaptive VDC is proposed in [18] to compensate for the effect of voltage drops across feeder impedances. In [19], a self-adjusting nominal voltage based modification in the VDC is proposed to improve the reactive power sharing amongst DER sources in an islanded microgrid. In the case of unbalanced load, [20] has proposed an improved control scheme courtesy of multiple inductor current feedback schemes combined. The control scheme ensures system operation in stable condition while maintaining the power quality criterion. In the VDC, for reference output power,

$$P_{ref} = G(s)[V_{ref} - (\frac{\omega_{LP}}{S + \omega_{LP}})V_{dc}]V_{dc} \tag{1}$$

$$I_{ref} = \frac{P_{ref}}{V_s} \tag{2}$$

where V_{dc} is the converter output voltage, ω_{LP} is the cut off frequency of Low Pass filter, V_{ref} is the voltage reference, I_{ref} is the current reference for each converter, and V_s is the dc source voltage. DER based microgrid's droop control is based on the droop characteristics of synchronous generators in a large power system. The concept of the control characteristics is that when the voltage and frequency of the grid decreases, the active and reactive power within the system also reduce. Distributed generator's (DG) output frequency and voltage are determined as [21]:

$$f = f' - m_p(P - P') \tag{3}$$

$$V = V' - n_q(Q - Q') \tag{4}$$

where f$'$ is DG's output frequency and V$'$ is the DG's output voltage magnitude at zero loading. P and Q are the measured active and reactive powers of the DG, P$'$ is the active power reference and Q$'$ is the reactive power reference. Due to the primary control, the voltage, frequency, and magnitude shift from the rated values and brings about the importance of secondary controlling actions.

2) Secondary Control Strategy: The secondary control scheme is implemented for the sake of monitoring the microgrid. The global frequency and local voltage are stable due to control strategies implemented in the secondary control. The secondary control with communication structure is laid over the primary control strategy. Reactive power-sharing, accurate frequency regulation, and power quality compensation are some of the additional goals of secondary control strategy [22].

The secondary control performs a comparison between rated voltage and frequency to the respective measured values and sends the calculated error as an input to the PI controller. The PI controller compensation signals added to the droop settings of DERs are as follows [23]:

$$\delta_i^{\omega} = K_{pc}(\omega^* - \omega_{bus}) + K_{ic}\int(\omega^* - \omega_{bus})dt \qquad (5)$$

$$\delta_i^{v} = \alpha_{pc}(V^* - V_{bus}) + \alpha_{ic}\int(V^* - V_{bus})dt \qquad (6)$$

where K_{pc},K_{ic} are PI control parameters for angular frequency and α_{pc},α_{ic} are PI control parameters for voltage control. Also, if the topology of the microgrid is known, it is possible to achieve the desired voltage profile by assigning a different reference to each DG. Thus, the secondary term in each DG can be calculated as follows:

$$\delta_i^{v} = \alpha_{pc}(V^* - V_i) + \alpha_{ic}\int(V^* - V_i)dt \qquad (7)$$

where V_i is the voltage reference for the converter i.

3) Tertiary Control Strategy: The tertiary control adjusts the voltage set points and consequent power entering or leaving the microgrid while it is operating in conjunction with other entities [14]. The bus voltages are regulated to adjust the individual DER contribution to power-sharing among microgrids. Power-sharing is controlled optimally and economically as a result of the tertiary control.

The highest level of control, the tertiary control, compares the grid's active and reactive power to the reference points. This level of fast-responding control assists in precise power sharing while mitigating maintenance cost of the system [24]. The tertiary control absorbs real power during the occurrence of a fault, such that the microgrid frequency falls to a certain limit, resulting in fault clearance by disconnection. The tertiary control also performs the real and reactive power sharing between entities by feeding the error value to the secondary PI controllers. The error value is estimated using differences between measured active powers, reactive powers, and respective desired values demonstrated in Fig. 1.

B. Frequency Response of DER Based Microgrid

The preceding sections provided an overview of the hierarchical control strategies within a microgrid. In this section, we will provide a review focusing on the frequency response of DER based microgrid. With the implementation of intermittent renewable energy sources, alongside power electronic converters in DERs, a microgrid is susceptible to relatively large frequency deviations. It is important that control systems regulate the frequency and prevent interruptions, especially with DER sources. A review on the prominent control strategies for microgrid frequency regulation is presented as follows:

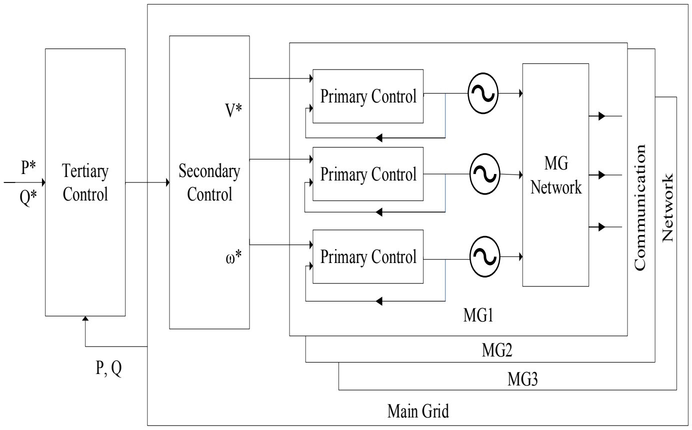

Fig. 1. Schematic of Microgrid Hierarchical Control Strategies [14]

1) Frequency Response Improvement using Hierarchical Control Strategies: Primary frequency control is responsible for halting the initial decrease and restoring the frequency under disturbances. Primary frequency control occurs at the level of individual controllers that are often droop-based as described in section II-A1. As opposed to the droop-based primary control methods previously described, [25] presents a sparse communication network-based frequency regulation where an individual controller processes its local and neighbors information to update its voltage magnitude and frequency. [26] presents an upgrade to the previous method with a distributed cooperative primary control based on a second-order quasi-Newton algorithm for better dynamic performance. Primary frequency regulation using the demand response (DR) strategy has been a topic for recent research with applications ranging from control of smart meters [27], wind farm auxiliary control [28], bioenergy cogeneration [29], and thermostatically controlled loads (TCLs) [30]. [31] has expanded the concept of TCLs into DR based primary frequency control for isolated microgrids. Networked microgrids are susceptible to higher frequency deviations due to large inrush currents, low inertia, and the presence of grid-following inverters. For networked microgrids, [32] presents a var-voltage optimization (VVO) based primary frequency control that engages the automatic voltage regulator (AVR) controls, on the sub-second timescale, to mitigate the deviations in frequency that occur in low-inertia networked microgrids. Another interesting primary frequency regulation method for networked microgrids is presented in [33], where an adaptive voltage and frequency control method is developed using distributed cooperative control and adaptive neural networks (ANN).

Secondary frequency control schemes of microgrids are mainly categorized into three types: centralized, decentralized, and distributed. In a centralized scheme, a central processor is required to undertake data communication and computation for all DGs, thus leading to excessive consumption of computation resources, while being susceptible to communication delays [34]. Also, it is difficult for decentralized secondary control to realize efficient coordination of all DGs based solely on its information. So, recent works have focused more on distributed secondary control for microgrid frequency regulation. [35]

proposed a distributed robust finite-time secondary voltage and frequency control multi-agent system in which inverter-based DGs serve as agents and DGs communicate with one another through a sparse communication network. Event-triggered communication mechanisms are widely employed to reduce the number of data exchange via communication networks. A distributed event-triggered cooperative control framework is presented in [36], [37] to realize power-sharing, frequency restoration, and voltage control in inverter-based isolated microgrids with the requirement of known initial supply and demand balance. As an improvement to these methods, [38] has presented an initialization free distributed control for active power-sharing and frequency regulation in an islanded microgrid under event-triggered communication.

2) Virtual Inertia for Microgrid Frequency Response: Virtual inertia has evolved as one of the solutions to the frequency regulation problem. Introducing the virtual inertia control into DG converters is a promising way to increase inertia within microgrids, to diminish fluctuation of the DC bus voltage, and to enhance the stability [39]. [40] presents virtual inertia emulation based on the derivative of frequency for improving system inertia and maintaining frequency stability. An interesting polynomial method called the coefficient Diagram Method (CDM) is applied as a robust virtual inertia controller to improve the frequency stability of an islanded microgrid.

Despite numerous papers focusing on independent virtual inertia controllers, the implementation of virtual inertia is mostly in conjunction with the virtual synchronous generator (VSG). VSG control possesses dynamic attributes of the synchronous generator (SG) as well as establishes virtual inertia support during instability while making sure the steady-state droop characteristics are preserved [41]. Also, since the inverter-based DGs are not limited by physical constraints as SGs, the inertia and damping parameters are flexibly designed in real-time [42]. Fig. 2 shows the synchronous machine model for VSG implementation. In recent works, as opposed to the constant inertia of conventional VSG, adaptive virtual inertia is proposed in [42] that does not require the frequency derivative (df/dt) to realize the variable virtual inertia, which is sensitive to measurement. [43] focuses on the analysis of the frequency response characteristics of the AC side to directly regulate the AC frequency by the virtual inertia generated from both the energy storage device and the grid-connected inverter. Recent works have also focused on the implementation of VSG control using short-term energy storage methods. In [44], the energy storage is implemented on the DC-link of the full-converter wind turbines as the energy buffer between the wind generation and the grid interfacing VSG control.

To make the review more illustrative,a simulation-based study of these control strategies is presented in section VI. The conventional generator based microgrid is compared against the DER based microgrid with droop based primary control strategy and VSG implementation in the ESS. Also, the impact of grid interfacing of electric vehicles to microgrid frequency response is studied.

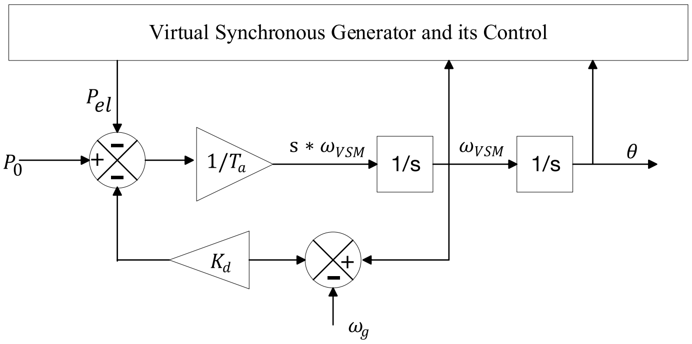

Fig. 2. Synchronous Machine Model for VSG Control Implementation [45]

III. ENERGY MANAGEMENT AND POWER QUALITY ENHANCEMENT OF DER BASED MICROGRID

A. Energy Management Systems

Energy management system (EMS) initiatives provide stability to the grid while microgrid operates in grid-connected mode or ensures optimal distribution of energy among the entities. Recent works have heavily focused on the EMS strategies like robust optimization, hierarchical control, chance and risk constrained programming, stochastic scheduling, mesh adaptive direct search, and metaheuristic approaches such as gravitational search, bacterial foraging [46].

Considering the intermittent nature of renewable sources, stochastic scheduling has been given much attention. A scheduling strategy upon the probability of islanding operation (PIO), new islanding operation index for renewable sources-based microgrid is determined which makes sure of an adequate level of spinning reserve for the system [47]. Considering random characteristics of renewable sources, a robust model has been formulated that includes scheduling of DERs to ensure primary and secondary reserves for limiting frequency fluctuation. The model also minimizes the total operation cost during frequency restoration of the microgrid system [48]. Strategies to optimize microgrid operation consisting of DERs [49] and ESS [50] are considered in terms of probabilistic cost minimization method. Also, supervisory EMS is proposed for coordination among the entities in a dynamic manner. In addition to ESS, EVs have been incorporated in the EMS studies. [51] has studied the possibility of EVs battery swapping using a bi-level optimized scheduling among microgrid and battery swapping stations. The strategy successfully minimizes the total cost including exchanged power between microgrids, renewable sources, and storage degradation.

Controller-based accurate power-sharing among distributed generators while considering non-linear load and source characteristics such as droop strategy is proposed [52], which makes use of sliding mode control to offset disturbances from sources and droop characteristics are represented through the fuzzy model. The work in [53] presents a detailed review of the microgrid supervisory controller (MGSC) based EMS techniques to improve the accuracy of load power-sharing and efficiency of the whole system. [54] presents a review on fuzzy logic approaches to design the control strategies of the microgrid EMS under two scenarios: the first one assuming that forecast of generation and consumption is not available, and the second one using the forecasted data. As the primary objective of energy management within the power system architecture is to optimize various operations, they are categorized into two classes: one refers to scheduling and the other as planning objectives [55]. A risk constrained stochastic framework has been presented that includes the procurement of energy generated by DERs be provisioned at operator's maximized profit while taking system reliability factors into account [56]. The management strategy is formulated for a cooperative microgrid in chance-constrained model predictive control (CCMPC) [57]. For the sake of optimized and allowed power exchange among grid and microgrids, a joint probabilistic constraint has been formulated.

In the DER based microgrid case, instead of startup and shutdown of generators - unit commitment of sources depends on accurate day-ahead forecasting about resource calculation and scheduling of sources to cater for load demand [58]. The unit commitment problem in earlier works involve robust optimization with a focus on security constraints [59], and network constraints [60]. Dynamic programming for unit commitment, improved genetic algorithm [61], and particle swarm optimization (PSO) [62] are utilized in solving unit commitment. Due to the advantage of almost no assumptions made in the PSO algorithm, the metaheuristic algorithm is quite efficient in solving unit commitment problems with large-sized sample space consisting of probable solutions [63].

B. Power Quality Enhancement

DER based microgrids feature various power electronics-based semiconductor devices such as converters, charge-discharge controllers, bi-directional power flow between intermittent source side and dynamic characteristics conserving load. Due to the variable attributes, the consumers connected to the microgrid encounter negative impacts on power quality (PQ). Usually, the PQ issues arise in the form of harmonics, flicker, unbalanced conditions of the system, and sudden surges [64]. PQ improvement can be defined as maintaining the distribution of power shape as close to sinusoidal power upon rated parameter values.

Various control strategies are proposed with the objective of PQ improvement, especially harmonics. [65] proposes a technique to mitigate negative effects in microgrid PQ due to intermittent nature of photovoltaic generation using a mathematical model based on the adaptation of proportional resonant (PR) and quasi-proportional resonant (QPR) controllers. On the controller level, [66] has proposed a repetitive controller for voltage harmonic mitigation of VSI-based islanded microgrids. A proposed control technique which performs harmonic current distribution and voltage harmonic compensation through a sole loop is based on the objective to achieve reference voltage that is obtained as the output of a droop controller [67]:

$$V_{DG_j}^{harm} = -V_{PCC}^{harm} * K_j^{harm} \tag{8}$$

where V_{PCC}^{harm} and K_j^{harm} represent the harmonic voltage and positive gain at PCC, respectively. The coefficient of harmonic droop controller a_j for DG unit j:

$$a_1 Q_{1-rated}^{harm} = a_2 Q_{2-rated}^{harm} = \cdots = a_m Q_{m-rated}^{harm} \tag{9}$$

where $Q_{j-rated}^{harm}$ is rated capacity of harmonic energy for each DG unit and the gain:

$$G_{harm} = \frac{a_0}{HD_{Max}} \tag{10}$$

where, a_0 is highly sufficient tuning for harmonic droop coefficient, HD_{Max} maximum voltage harmonic distortions for any DG unit 'j' the a_j is:

$$a_j = \frac{a_0}{Q_{j-rated}^{harm}} \tag{11}$$

1) Unified Power Quality Conditioner: Emphasizing various PQ improvement solutions within DER sources based microgrid, integration of custom power devices such as Unified Power Quality Conditioner (UPQC) are becoming more significant. The formation of UPQC takes place with a back-to-back connection in series and parallel combinations of active power filters. The series component contributes to maintaining the required load voltage and minimizes voltage sags, swell, unbalance, and any harmonics introduced. Reduced power factor, harmonic currents, and unbalance due to load are dealt with by parallel combinational component [68]. The UPQC and DER sources can be connected in DC link so that during PQ interruptions, UPQC can inject voltage or current for crucial load demands to avoid any disruptions. Due to this implementation, voltage interruption is resisted through compensation via UPQC while the DERs act as energy sources within the microgrid. The UPQC is integrated into the microgrid either through a DC-link coupling or separately. The pros and cons of the two integration techniques are described in Table I.

TABLE I
COMPARISON OF UPQC INTEGRATION TECHNIQUES FOR DG SYSTEM

Technique	Advantages	Disadvantages
DER-UPQC (Connected Through DC Link)	Compensation of voltage and active power to avoid system interruption, islanded mode operation possible, PQ improvement cost is reduced.	Complex control, difficult multi-level or multi-module mode capacity enhancement.
DER-UPQC (Separated)	Comparatively easier control, easier multi-level or multi-module mode capacity enhancement, compensation of active power is possible.	Compensation of voltage as well as islanding mode operation might not be possible, PQ improvement cost is high.

UPQCs can be placed within the microgrid both on grid-integrated or grid-isolated mode. To obtain capacity enhancement through multilevel topologies, the following options are prominent:

1) Multi-level converter based UPQC
2) Multi-module converter based UPQC

3) Multi-module (power cell) unit based UPQC

The advantages and disadvantages of these topologies are presented in Table II. Variants of the UPQC for PQ improvement have been a focus of research in recent years. There has been a particular interest in solar PV integration of UPQC (PV-UPQC), with [69] proposing an improved synchronous reference frame control based on moving average filter is used for extraction of load active current component. [70] presents an upgrade to the previous method with a battery integrated PV-UPQC to facilitate a seamless transition between UPQC operating modes under PQ disturbances. In [71], a variant of UPQC, the open UPQC (UPQC-O) has been implemented with an on-line operational optimization approach to determine the optimal reactive power under varying load demand of a distribution network. Research in [72] has presented an adaptive neuro-fuzzy based controller interface to replace the conventional PI for better control of harmonics in the microgrid. Considering the load influence of EVs, [73] has proposed a double-layer DC structured microgrid to connect EVs in parallel and restrain DC voltage variations in the UPQC. The work modifies control of the UPQC to address the charging of EVs by using power from the grid directly while compensating for PQ issues.

TABLE II
ADVANTAGES AND DISADVANTAGES OF DIFFERENT UPQC TYPES

Types of UPQC	Advantages	Disadvantages
Multi-level Converter based	Possible to obtain high voltage and current, multiple ways to build-up.	Different level voltage unbalancing, mandatory central control requirement, difficult capacity expansion.
Multimodular transformer-less	Cost reduced due to no need of series transformer, easier capacity expansion than Multi-level Converter based.	Requirement of higher number of switching devices, mandatory central control requirement, high switching and conduction loss, modules may not work at highest rating
Multimodular (power cell)	Module operation at maximum rating, can operate as centralized or decentralized, reduced conduction loss.	Increased switching loss, transformer and system loss.

2) Role of Energy Storage in Microgrid Power Quality Enhancement: The energy storage systems (ESS) are among the most simplistic and suitable forms for microgrid PQ enhancement. Since the ESS's fast efficiency and zero-emission with high power density lead to quick response, they are a viable option for PQ restoration in DER based microgrid. Various kinds of ESS are subjected to study in PQ improvement. Battery energy storage systems (BESS) are connected to the grid through converters which allow flexible control over power flow in both directions [74]. System imbalances such as voltage deformations and fluctuations due to reactive power disparity during intermittent power supply by the DER sources or lack of VAR compensation encountered in power lines are investigated to be sufficiently resolved by application of ESS [75]. Apart from BESS, state-of-the-art ESS such as the superconducting magnetic energy storage system (SMES) application in the point of common coupling (PCC) to perform reactive power compensation has been conducted successfully. The stable DC-link of BESS helps to get rid of voltage harmonics by canceling the harmonic current in the form of offsetting through opposite phase equal magnitude harmonic current [76].

IV. IMPACT OF ELECTRIC VEHICLES AND ENERGY STORAGE SYSTEMS ON DER BASED MICROGRID

There has been a rapid growth in the penetration of EVs into power systems in recent years. EVs are environmentally preferred over conventional fuel-based transportation systems, along with their ability to take part in the bi-directional power flow to the grid [77]. The most feasible mean to implement large-scale EV integration into the grid is through a microgrid structure. Along with EVs, the integration of ESS in microgrids is growing due to their ability to alleviate the intermittency associated with DER sources. In this section, a review of the recent works on the impact assessment of EVs and ESS in various aspects of the microgrid is presented.

A. Impact of EV Control Strategies

EVs can contribute to primary frequency control and attain characteristics of both load and storage/distributed source that leads to the concept of vehicle-to-grid (V2G) [78]. Under transients, the voltage and frequency restoration takes place according to the cumulative charging/discharging capacity of EVs. As frequency regulation via EVs depends on the state of charge of EV storage, the smart algorithm based metering system in Fig. 3 is most suitable for EV integration [79]. This operation strategy plugs off EV from microgrid during limited power state and is dependent on frequency variation constraint limit while the number of EV in the grid is changing. Disconnection of EV occurs by reducing the charging/discharging current, and the smooth transition process maintains frequency regulation.

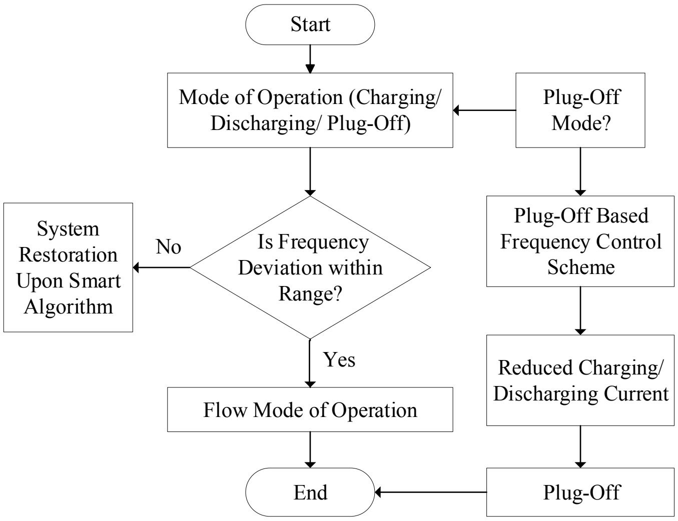

Fig. 3. Smart Algorithm Metering based Frequency Regulation by EV [79]

EV integration into microgrid provides greater flexibility in controlling supply and demand characteristics in terms of real-time pricing on charging and discharging, peak shaving, as well as filling valley over other methods of stability restoration [80]. The storage attributes of EVs such as indeterminate mobility, the correlation between power system aggregator, EV based modeling to maximize the profit for ancillary service providers, and participation of EVs into microgrid are discussed referring to frequency restoration and peak demand shaping. Distributed control techniques such as master-slave control of EV power for frequency fluctuations on a real-time basis are studied [81].

Among the control strategies, neuro-fuzzy inference system and dual droop based synchronized strategy are the most fitting methods which overcome shortcomings of distributed control techniques by adapting droop based control of EV energy storage to regulate power and frequency deviations [82]. Flexible/decentralized charging and discharging algorithms are implemented for EV storage that can be used for back-up during peak and low load demand, mitigating the intermittency of DERs, and minimizing the cost of energy for EV participants [83]. Adaptive applications of the fuzzy logic controller are implemented according to change in the state of EV battery storage charge, source current, load, and tariff. It ensures active power-sharing among multiple microgrids and EVs in a satisfactorily reduced limit of total harmonic distortions (THD) [84]. Further, the studies conclude that the independent system operator (ISO) payment is higher in coupled and decoupled energy market with EVs participation [85]. Future tasks such as regulation of current in vehicle-to-grid (V2G), proper communication infrastructure for real-time control of network functions, application of EV corresponding to real-time monitoring, degradation of EV storage in bi-directional power flow, etc. require to be further developed regarding EV's effective integration into DER based microgrid.

B. Role of ESS in Microgrid Stability Enhancement

Transient instability during islanded mode operation of DER based microgrid is an issue which is caused due to the lack of synchronous generation. Impact of ESS in such circumstances have been investigated leading to significant improvement of transient stability phenomenon [86]. Control methods have been proposed in [76] that switch operation of battery ESS among multiple states to reduce system instability. Modes such as the Genset support mode functions, along with the loads, for the sake of balancing reactive power compensation takes place and generators are driven within the specified needed power range [87]. [88] has studied the application of ESS control strategies in case of unbalanced loads within DER based microgrid, where the loads are considered to be balanced in the ESS control scheme during grid-forming mode .

Apart from the battery energy storages, state-of-the-art storage technologies such as supercapacitors are implemented in DER based hybrid microgrid architecture. The control strategies of supercapacitors have also been studied for storage applications of DER based microgrid [89]. The proposed approach adds a virtual RC unit in series with DC bus and power converter using a loop of virtual impedance which decouples flow of power to the supercapacitor. The approach renders the supercapacitors to act as a storage as well as constant source. Research in [90] has proposed a voltage controller for DC-link of a supercapacitor that provides sufficient gain margin and phase margin at all supercapacitor operating voltages to enhance microgrid reliability.

V. APPLICATIONS OF DISTRIBUTED ENERGY RESOURCES AND ELECTRIC VEHICLES IN RELIABILITY OF HYBRID MICROGRID

Due to the intermittency in variable renewable energy sources driven power generation, much emphasis has been given to the reliable operation of microgrids. The assessment of reliable operation of interconnected/standalone hybrid DER in terms of reliability indices have been performed extensively. The review in this section is segmented for general microgrid reliability assessment under the influence of DERs and influence of EVs and ESS:

A. Microgrid Reliability Assessment under DER influence

DERs introduce instability in the power system that could lead to serious occurrences such as blackouts. Some of the recent works have focused on optimal penetration of variable renewable sources under reliability constraints [91], unit commitment along with energy storage in reliable operation of hybrid renewable sources based microgrid [92], stability analysis according to power load characteristics [93], and reliability assessments of microgrid considering cyber-physical aspects [94]. In evaluating reliable operation aspects of renewable energy-based microgrid, source reliability assessment is considered - where alongside the reliability indices, interruption cost and demand/supply cost are taken into account. Multiple topologies of networks are examined for reliability as per the proposed method [95]. As microgrids are usually placed near the distribution side, reliability analysis takes the unavailability of distributed generators and mobile generation into consideration where two primary phases of load demand, peak and off-peak hours are subjected to study. The ultimate goal of improving the architecture's reliability through continuous power supply to load within the microgrid architecture located in the distribution side is studied [96]. Sensitivity analysis of reliability measures is performed in the case of DER based multiple interconnected microgrid structure, where it is examined that wind resource modeling is an important factor that can affect the reliability indices [97]. The proposed approach optimizes the placement and size of wind farms to achieve the best reliability index values. Recent works have also focused on achieving maximum grid profit through consideration of demand response (DR) applications into reliability and economic analysis [98].

B. Impact of EVs in Microgrid Reliability

EVs have a two-way impact on the microgrids. With a large population of EVs, the overall load profile of the microgrid will change significantly. On the other hand, the introduction of EVs in the microgrid initiates opportunities to store and regulate power generated from highly intermittent RERs, contributing to primary frequency control using vehicle-to-grid (V2G) [99]. The load and source-based characteristics of EV are found to be contributing effectively to power quality improvement, load reduction, etc. alongside the demand side management that proves EV integration is conductive for microgrid reliability enhancement [100].

There are two possible integration modes of EV fleet into the microgrid systems:

1) Plug-in mode (dispersed electrical load/storage units)
2) Battery exchange (BE) mode

Reliability assessment of power system with different charging strategies under plug-in mode are studied in [101]. The reliability impacts of plug-in hybrid EVs (PHEVs) on the residential distribution systems is presented [102]. The reliability assessment of microgrids with EVs in BE-mode less studied compared to plug-in EVs. Along with the inherent advantage of fast charging, BE mode has advantages of no maintenance issues for customers and use of central BE-station as ESS [103]. The central BE-station acts as ESS in this mode, yielding considerable advantage in standalone microgrids, primarily in alleviating the high generation intermittency of RERs [104]. Reliability model for EV in BE-mode is presented [105] as well as distribution system reliability assessment is conducted while EVs are operated in BE mode [103].

VI. MICROGRID SYSTEM FREQUENCY RESPONSE SIMULATION RESULTS

Section II-B1 provided a review of the existing works on power electronic converter control schemes for better frequency response of the microgrid. This section provides a simulation study on the impacts of DER units and EVs on the microgrid system frequency regulation. Some of the control strategies reviewed in section II-B1 are implemented in a standalone microgrid system to verify and analyze the DER's impact on microgrid frequency regulation.

The modified vehicle-2-grid (V2G) system in MATLAB/Simulink is used to study the microgrid frequency regulation. The test system has one diesel generator of 15 MW, one wind farm of 4.5 MW, and a PV farm of 8 MW that supply a 10 MW residential load. The intermittent nature of PV, wind farm, and load is considered in the simulation. To simulate a load step increase, a 150 KW asynchronous motor is turned on, and the system frequency response is examined. The frequency response strategies discussed in [106] and section II-B1 are introduced in the test system. Also, 100 EVs are introduced in the microgrid, each having a (40 KW) battery capacity. The simulation scenarios considered to investigate the effects of DER, ESS, and EVs in the system frequency regulation are as follows:

- Scenario 1: The default system is modified to include the control strategies for the PV and wind farm as discussed in section II. The primary and secondary frequency control strategies are implemented in the PV and wind farms.
- Scenario 2: In this scenario, renewable sources are completely excluded from the system. An additional diesel generator of 10 MW capacity replaces the PV and wind farm. The system will have the highest inertia in this scenario along with lower frequency regulation constant.
- Scenario 3: The effects of the implementation of virtual synchronous generators are investigated in this scenario. An ESS of 160 KW is introduced in the PV farm with a full state of charge (SOC). The ESS should provide virtual inertia to the system and improve frequency response.
- Scenario 4: The effects of EVs in the microgrid frequency response is illustrated in this scenario. The EVs will be in grid regulation mode when they are connected to the grid. The regulation capacity depends upon the state of charge of the vehicle batteries and the number of vehicles connected to the grid (vehicles on the road are not connected).

From the simulation results, several observations were made:

- The intermittent nature of DERs and low system inertia degrade the system frequency response as seen in Fig. 4. Compared to scenario 2 where two diesel generators are present, scenario 1 experienced a larger frequency deviation. The maximum frequency deviation with scenario 2 is 0.03 Hz while it is 0.06 Hz in scenario 1. The inclusion of primary and secondary frequency response was able to keep the frequency deviation within safe limits in scenario 1. Also, as seen in Fig. 5 the inclusion of renewable sources lowered the system ROCOF. The reduced ROCOF could hamper the system when protective df/dt relays are employed.
- The inclusion of ESS in the PV farm in scenario 3 significantly improved the system frequency response. The virtual inertial circuit in the ESS emulated the conventional generator inertia and reduced the maximum frequency deviation to 0.05 Hz. The ROCOF also improved with the inclusion of VSG based ESS in the system.
- The introduction of EVs in the grid was able to improve the system frequency response. Out of 100 EVs, 90 were operating in regulation mode i.e. connected to the grid. The lower SOC batteries would continue to charge with excess system power. Under load disturbance, the batteries discharge to support the microgrid. The frequency response circuit deployed in the EV batteries triggers under contingencies. With the EVs, the frequency deviation reduced to 0.045 Hz and the ROCOF improved.

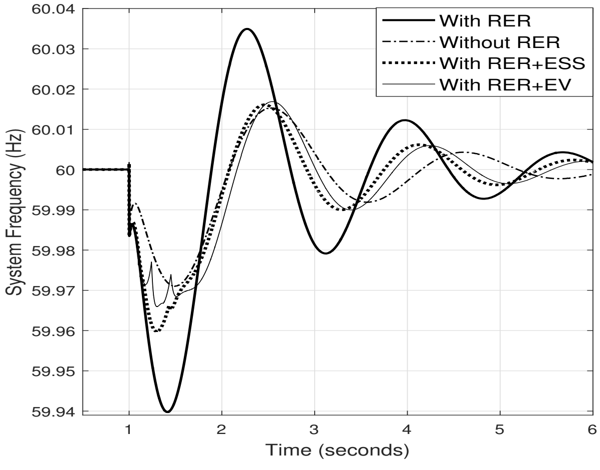

Fig. 4. System Frequency Deviation Under Various Simulation Scenarios.

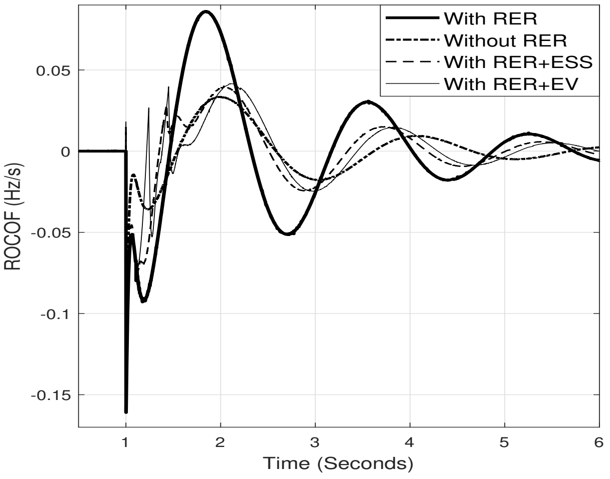

Fig. 5. System ROCOF Under Various Simulation Scenarios.

To investigate the detailed effect of EV in microgrid frequency response, the system frequency deviation under varying vehicle integration is implemented. The system frequency nadir is measured with a varying number of vehicles in regulation mode. Fig. 6 shows the results of the simulation. As seen from the results, the system would experience constant frequency deviation until the regulation power demand was satisfied. However, when the number of vehicles connected to the grid was less than 13, the system frequency deviation would increase as the regulation power reduced. Even though the total capacity of vehicles connected was $13 * 40\ KW$ and regulation power demand was $445\ KW$, the EV batteries could not supply the required power due to a lower state of charge. Hence, the system experiences a higher frequency deviation as fewer cars are connected to the system. From the simulations, it can be seen that with higher penetration of EVs in the microgrids, it is important to schedule vehicle operation so that the system frequency response can improve. This simulation considered the use of plug-in EVs. Next, we will observe the microgrid system reliability as centralized battery-exchange (BE) based EVs are introduced in the microgrid.

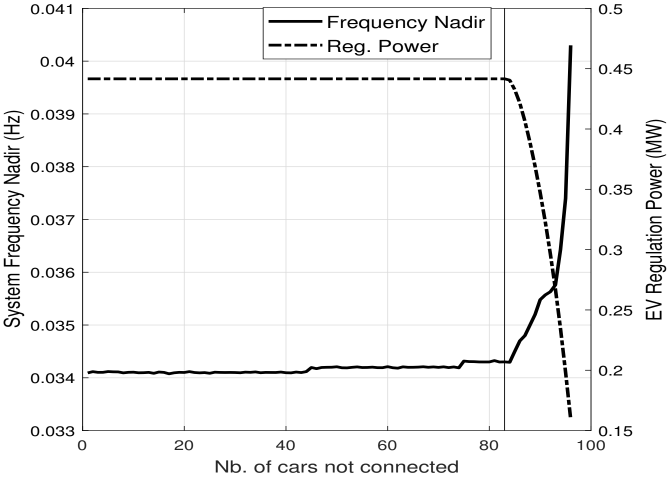

Fig. 6. Frequency Nadir and Regulation Power with Varying EV Integration.

VII. MICROGRID SYSTEM RELIABILITY EVALUATION IN THE PRESENCE OF DERS

In this section, the standalone microgrid reliability assessment is performed in the presence of DERs. The simulation will verify the results of reliability assessment techniques reviewed in section V. In section VI, simulations were performed in the presence of the prominent plug-in EVs. In addition to assessing the impacts of DERs in the microgrid, this simulation will investigate the advantages of a central (BE) station based EVs in the microgrid. Since the BE-station behaves as an ESS under grid interaction, the combined effect of EV and ESS can be assessed with this method.

A. Modeling of BE-station based EVs

A simplified user behavior extraction model is constructed based on [107], [108]. The EV user behavior is extracted and modified to form a time-series load profile of the EV. In addition to the intermittency of wind and PV power, the varying load from EV is evaluated at every time step (one hour).

The 2017 National Households Travel Survey (NHTS) [109] is used as the traveling pattern database in this paper. It is built up by the U.S. Department of Transportation, which collects representative traveling information from the U.S. households, such as the start/end time of a trip and trip distance, etc. The daily travel pattern of $250,000$ cars has been extracted from the database. The capacity of the central BE station is $100\ MW$ and there are 30000 EVs in the system. The operation strategy for the central BE-station is chosen to be similar to the ESS operation strategy proposed in [110]. However, the major difference between the BE stations and ESS is that the BE-station continuously discharges to provide charging facility to the EV customers.

For a detailed reliability assessment, the effect of controlled EV battery exchanges is also studied. Fig. 7 shows the plot of 24 hr average driving miles for all EVs in consideration and average load of the IEEE-RTS system. As seen from the figure, the average driving miles of EV users almost coincide with the peak load of the system. Since a larger number of battery exchanges occur after higher driving miles, the discharge maximum of BE station and load of RTS tend to coincide. This condition is not favorable for microgrid reliability since the EVs contribute to a larger peak load during the day. To alleviate this problem, a higher discharge limit for battery exchange is permitted during the off-peak hours. In the real-world, this can be realized by providing incentives for battery exchange during off-peak hours. From Fig. 8, it can be seen that the load profile smoothens by a large amount when the off-peak strategy is improved. This should contribute to system peak load shaving and reliability improvement.

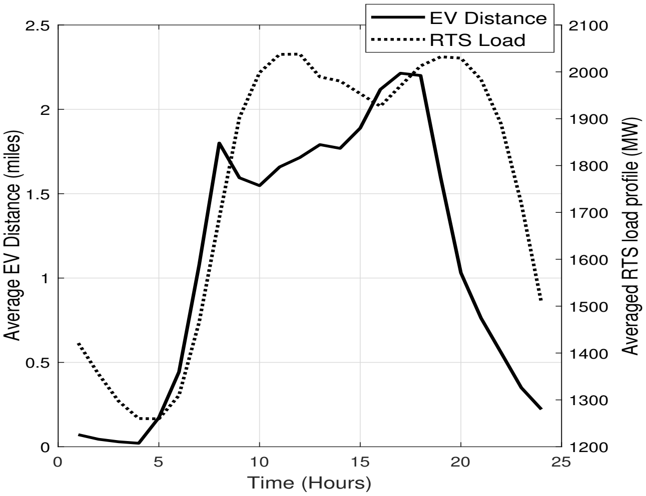

Fig. 7. Average EV Distance and RTS Load Profile.

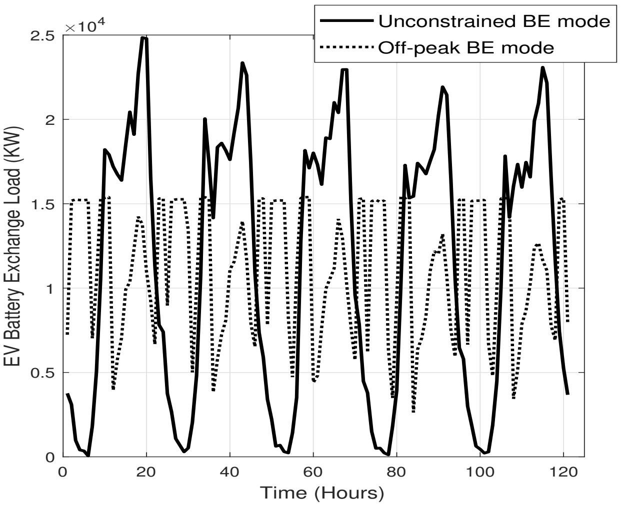

Fig. 8. 5-day Load Profile for Uncontrolled vs Controlled Battery Exchange.

B. Modeling of DERS and Other Simulation Settings

The reliability assessment is performed on the IEEE RTS-79 system [111]. The original IEEE RTS-79 system includes 32 conventional generators with a total capacity of 3405 MW, and the annual peak load of the system is 2850 MW. The two-year solar radiation data is extracted from the National Renewable Energy Laboratory (NREL) data sets from [112] and mean clustered into 1-h interval. Each solar farm has a string system topology with 50 solar arrays, each of 60 KW. The wind speed data is extracted from [113]. The cut-in, rated, and cut-out speeds of wind turbines are 6, 12, and 25 m/s, respectively [114]. Each wind farm has 80 MW rated power with 10 identical wind turbines. The EV data is obtained using the procedure described in section VII-A. The power output model of PV farm is constructed as per the procedure in [115] and wind power output model is constructed using [116]. The reliability indices evaluated are the Loss of load probability (LOLP), Loss of load frequency (LOLF), Hourly loss of load expectation (HLOLE), Energy demand not satisfied (EDNS), and Expected Unserved Electrical Energy (EUEE) [117].

C. Reliability Assessment Results

The simulation scenarios and the results obtained have been described as follows:

Base Case and Scenario 1: For the base scenario, the system is assessed with zero renewable energy penetration. Table III shows the results for the base scenario. In scenario 1, five PV farms (150 MW) and two wind farms (160 MW) are added to the existing system. The results in Table. III illustrates that the reliability indices (LOLP, LOLF, and EDNS) have considerably improved. It indicates that the addition of renewables in the existing microgrids will have a positive effect on system reliability despite their generation intermittency.

Scenario 2: This scenario illustrates the case when DERs displace the existing conventional sources. In this case, the 400 MW generator is replaced by five additional PV farms and four wind farms (total renewable generation capacity is 540 MW). As seen from the results, the system reliability indices degrade considerably even when the replacing DERs have a larger capacity than the existing generator. This scenario illustrates the challenge for renewable-based microgrid when conventional sources need to be displaced.

Scenario 3 and 4: In these scenarios, the EVs are introduced in the RTS system with different exchange strategies. In both cases, a central BE station of 100 MWh is included along with 30000 electric vehicles in the system. In scenario 3, the battery exchange for EV users is uncontrolled i.e. whenever the EV battery SOC drops below 10% of full capacity, the BE station replaces the battery. As seen from the results, the reliability indices improve significantly compared to scenario 2. The BE station acts as an ESS and supports the grid when there is an outage. Scenario 4 presents the results when the off-peak controlled battery exchange strategy in section VII-A is implemented. In this scenario, the total energy consumed by vehicles increased to 95760 MWh compared to 95294 MWh in scenario 3. It is because drivers were encouraged to exchange batteries in off-peak hours at a higher SOC (20% of full capacity). Even with higher energy consumption, the off-peak exchange strategy managed to improve system reliability even further since it helped reduce overall system peak load.

TABLE III
SEQUENTIAL MONTE-CARLO SIMULATION RESULTS

Index	LOLP	HLOLE h/yr	LOLF f/yr	EDNS MW/yr	EUEE MWh/yr
Base Case	0.00115	10.226	2.0140	0.1473	1290.067
Scenario 1	0.00067	5.891	1.3328	0.0823	721.155
Scenario 2	0.00293	25.057	6.0432	0.3757	3290.801
Scenario 3	0.00257	22.429	4.9750	0.3495	3062.028
Scenario 4	0.00251	21.429	4.8731	0.3429	3003.582

The microgrid reliability assessment results agree with the results of works reviewed in section V. The results show that the addition of renewable sources to the existing system enhances the microgrid reliability. However, when the conventional generators are displaced, the renewable sources' intermittent generation has deleterious effects on system reliability. The introduction of BE- station based EVs can help improve the microgrid system reliability since the stations can discharge when the system generation is inadequate. Proper scheduling of grid interaction of EVs can enhance system reliability in addition to improved frequency response as verified in section VI.

VIII. CONCLUSION

Microgrid as a new concept that turns out to be distributed renewable energy resources (DER) conducive is growing worldwide. The structure brings about numerous advantages and applications of many smart grid attributes, along with opportunities to obtain resilient grid operation and diverse challenges to overcome. This paper reviews the concept and application of the DER based microgrid so far investigated in the research. The DER architecture proves to be feasible for the integration of renewable energy sources with the appropriate application of converter control strategies, energy management systems, and power quality improvement strategies. The review also shows that the DER based microgrids attain enhanced performance with appropriate interaction of EVs and optimized operation strategies of the ESS. The simulations in the paper agree with the results of the existing works on microgrid frequency regulation and reliability and emphasize the importance of EV and ESS interaction with the microgrid. The study should pave the way for researchers in developing insights regarding DER-based microgrid and its various attributes.

REFERENCES

[1] G. Mohy-ud-din, D. H. Vu, K. M. Muttaqi, and D. Sutanto, "An integrated energy management approach for the economic operation of industrial microgrids under uncertainty of renewable energy," *IEEE Trans. Ind. Appl.*, vol. 56, no. 2, pp. 1062–1073, 2020.

[2] P. S. Kumar, R. P. S. Chandrasena, V. Ramu, G. N. Srinivas, and K. V. S. M. Babu, "Energy management system for small scale hybrid wind solar battery based microgrid," *IEEE Access*, vol. 8, pp. 8336–8345, 2020.

[3] C. A. Cortes, S. F. Contreras, and M. Shahidehpour, "Microgrid topology planning for enhancing the reliability of active distribution networks," *IEEE Trans. Smart Grid*, vol. 9, pp. 6369–6377, Nov 2018.

[4] L. Mariam, M. Basu, and M. F. Conlon, "Microgrid: Architecture, policy and future trends," *Renewable Sustain. Energy Rev.*, vol. 64, pp. 477–489, 2016.

[5] A. Hirsch, Y. Parag, and J. Guerrero, "Microgrids: A review of technologies, key drivers, and outstanding issues," *Renewable Sustain. Energy Rev.*, vol. 90, pp. 402–411, 2018.

[6] R. K. Oueid, "Microgrid finance, revenue, and regulation considerations," *The Electricity J.*, vol. 32, no. 5, pp. 2–9, 2019.

[7] A. Cagnano, E. De Tuglie, and P. Mancarella, "Microgrids: Overview and guidelines for practical implementations and operation," *Appl. Energy*, vol. 258, p. 114039, 2020.

[8] M. M. Lubbad, N. H. El-Amary, and A. Y. Abdelaziz, "Sliding mode control for hybrid power sources micro-grid," in *2019 21st Int. Middle East Power Syst. Conf. (MEPCON)*, pp. 650–655, 2019.

[9] J. Wu and Y. Lu, "Adaptive backstepping sliding mode control for boost converter with constant power load," *IEEE Access*, vol. 7, pp. 50797–50807, 2019.

[10] Q. Tabart, I. Vechiu, A. Etxeberria, and S. Bacha, "Hybrid energy storage system microgrids integration for power quality improvement using four-leg three-level npc inverter and second-order sliding mode control," *IEEE Trans. Ind. Electron.*, vol. 65, pp. 424–435, Jan 2018.

[11] A. Pilloni, A. Pisano, and E. Usai, "Robust finite-time frequency and voltage restoration of inverter-based microgrids via sliding-mode cooperative control," *IEEE Trans. Ind. Electron.*, vol. 65, pp. 907–917, Jan 2018.

[12] M. Rezkallah, A. Chandra, B. Singh, and S. Singh, "Microgrid: configurations, control and applications," *IEEE Trans. Smart Grid*, vol. 10, no. 2, pp. 1290–1302, 2017.

[13] N. A. Ninad and L. A. C. Lopes, "Control of δ-y transformer based grid forming inverter for unbalanced stand-alone hybrid systems," in *2012 IEEE Electr. Power and Energy Conf.*, pp. 176–181, Oct 2012.

[14] A. Mohammed, S. S. Refaat, S. Bayhan, and H. Abu-Rub, "Ac microgrid control and management strategies: Evaluation and review," *IEEE Power Electron. Mag.*, vol. 6, no. 2, pp. 18–31, 2019.

[15] J. M. Guerrero, M. Chandorkar, T.-L. Lee, and P. C. Loh, "Advanced control architectures for intelligent microgrids—part i: Decentralized and hierarchical control," *IEEE Trans. Ind. Electron.*, vol. 60, no. 4, pp. 1254–1262, 2012.

[16] J. Kim, J. M. Guerrero, P. Rodriguez, R. Teodorescu, and K. Nam, "Mode adaptive droop control with virtual output impedances for an inverter-based flexible ac microgrid," *IEEE Trans. Power Electron.*, vol. 26, no. 3, pp. 689–701, 2010.

[17] W. Yao, M. Chen, J. Matas, J. M. Guerrero, and Z.-M. Qian, "Design and analysis of the droop control method for parallel inverters considering the impact of the complex impedance on the power sharing," *IEEE Trans. Ind. Electron.*, vol. 58, no. 2, pp. 576–588, 2010.

[18] H. Mahmood, D. Michaelson, and J. Jiang, "Reactive power sharing in islanded microgrids using adaptive voltage droop control," *IEEE Trans. Smart Grid*, vol. 6, no. 6, pp. 3052–3060, 2015.

[19] H. Mahmood, D. Michaelson, and J. Jiang, "Reactive power sharing in islanded microgrids using adaptive voltage droop control," *IEEE Trans. Smart Grid*, vol. 6, no. 6, pp. 3052–3060, 2015.

[20] W. Zhao, X. Ruan, D. Yang, X. Chen, and L. Jia, "Neutral point voltage ripple suppression for a three-phase four-wire inverter with an independently controlled neutral module," *IEEE Trans. on Ind. Electron.*, vol. 64, no. 4, pp. 2608–2619, 2017.

[21] M. Anwar, M. I. Marei, and A. A. El-Sattar, "Generalized droop-based control for an islanded microgrid," in *2017 12th Int. Conf. on Comput. Eng. and Syst. (ICCES)*, pp. 717–722, Dec 2017.

[22] J. W. Simpson-Porco, Q. Shafiee, F. Dörfler, J. C. Vasquez, J. M. Guerrero, and F. Bullo, "Secondary frequency and voltage control of islanded microgrids via distributed averaging," *IEEE Trans. Ind. Electron.*, vol. 62, no. 11, pp. 7025–7038, 2015.

[23] A. C. Z. de Souza and M. Castilla, *Microgrids design and implementation*. Springer, 2019.

[24] L. Meng, T. Dragicevic, J. C. Vasquez, and J. M. Guerrero, "Tertiary and secondary control levels for efficiency optimization and system damping in droop controlled dc–dc converters," *IEEE Trans. Smart Grid*, vol. 6, no. 6, pp. 2615–2626, 2015.

[25] V. Nasirian, Q. Shafiee, J. M. Guerrero, F. L. Lewis, and A. Davoudi, "Droop-free distributed control for ac microgrids," *IEEE Trans. Power Electron.*, vol. 31, no. 2, pp. 1600–1617, 2016.

[26] Z. Wang, W. Wu, and B. Zhang, "A distributed quasi-newton method for droop-free primary frequency control in autonomous microgrids," *IEEE Trans. Smart Grid*, vol. 9, no. 3, pp. 2214–2223, 2018.

[27] K. Samarakoon, J. Ekanayake, and N. Jenkins, "Investigation of domestic load control to provide primary frequency response using smart meters," *IEEE Trans. Smart Grid*, vol. 3, no. 1, pp. 282–292, 2011.

[28] S. Wang and K. Tomsovic, "Fast frequency support from wind turbine generators with auxiliary dynamic demand control," *IEEE Trans. Power Syst.*, vol. 34, no. 5, pp. 3340–3348, 2019.

[29] A. K. Barik and D. C. Das, "Coordinated regulation of voltage and load frequency in demand response supported biorenewable cogeneration-based isolated hybrid microgrid with quasi-oppositional selfish herd optimisation," *Int. Trans. Elect. Energy Syst.*, vol. 30, no. 1, p. e12176, 2020.

[30] Q. Shi, F. Li, G. Liu, D. Shi, Z. Yi, and Z. Wang, "Thermostatic load control for system frequency regulation considering daily demand profile and progressive recovery," *IEEE Trans. Smart Grid*, vol. 10, no. 6, pp. 6259–6270, 2019.

[31] W. Mendieta and C. A. Cañizares, "Primary frequency control in isolated microgrids using thermostatically controllable loads," *IEEE Trans. Smart Grid*, 2020.

[32] K. P. Schneider, N. Radhakrishnan, Y. Tang, F. K. Tuffner, C.-C. Liu, J. Xie, and D. Ton, "Improving primary frequency response to support networked microgrid operations," *IEEE Trans. Power Syst.*, vol. 34, no. 1, pp. 659–667, 2018.

[33] D. O. Amoateng, M. Al Hosani, M. S. Elmoursi, K. Turitsyn, and J. L. Kirtley, "Adaptive voltage and frequency control of islanded multi-microgrids," *IEEE Trans. Power Syst.*, vol. 33, no. 4, pp. 4454–4465, 2017.

[34] S. Liu, X. Wang, and P. X. Liu, "Impact of communication delays on secondary frequency control in an islanded microgrid," *IEEE Trans. on Ind. Electron.*, vol. 62, no. 4, pp. 2021–2031, 2014.

[35] N. M. Dehkordi, N. Sadati, and M. Hamzeh, "Distributed robust finite-time secondary voltage and frequency control of islanded microgrids," *IEEE Trans. Power Syst.*, vol. 32, no. 5, pp. 3648–3659, 2016.

[36] S. Weng, D. Yue, C. Dou, J. Shi, and C. Huang, "Distributed event-triggered cooperative control for frequency and voltage stability and power sharing in isolated inverter-based microgrid," *IEEE Trans. Cybern.*, no. 99, pp. 1–13, 2018.

[37] M. Chen, X. Xiao, and J. M. Guerrero, "Secondary restoration control of islanded microgrids with a decentralized event-triggered strategy," *IEEE Trans. Ind. Inform.*, vol. 14, no. 9, pp. 3870–3880, 2018.

[38] L. Ding, Q.-L. Han, and X.-M. Zhang, "Distributed secondary control for active power sharing and frequency regulation in islanded microgrids using an event-triggered communication mechanism," *IEEE Trans. Ind. Inform.*, vol. 15, no. 7, pp. 3910–3922, 2018.

[39] W. Wu, Y. Chen, A. Luo, L. Zhou, X. Zhou, L. Yang, Y. Dong, and J. M. Guerrero, "A virtual inertia control strategy for dc microgrids analogized with virtual synchronous machines," *IEEE Trans.Ind. Electron.*, vol. 64, no. 7, pp. 6005–6016, 2016.

[40] H. Ali, G. Magdy, B. Li, G. Shabib, A. A. Elbaset, D. Xu, and Y. Mitani, "A new frequency control strategy in an islanded microgrid using virtual inertia control-based coefficient diagram method," *IEEE Access*, vol. 7, pp. 16979–16990, 2019.

[41] J. Liu, Y. Miura, and T. Ise, "Comparison of dynamic characteristics between virtual synchronous generator and droop control in inverter-based distributed generators," *IEEE Trans. Power Electron.*, vol. 31, no. 5, pp. 3600–3611, 2015.

[42] X. Hou, Y. Sun, X. Zhang, J. Lu, P. Wang, and J. M. Guerrero, "Improvement of frequency regulation in vsg-based ac microgrid via adaptive virtual inertia," *IEEE Trans. Power Electron.*, vol. 35, no. 2, pp. 1589–1602, 2019.

[43] K. Shi, H. Ye, W. Song, and G. Zhou, "Virtual inertia control strategy in microgrid based on virtual synchronous generator technology," *IEEE Access*, vol. 6, pp. 27949–27957, 2018.

[44] Y. Ma, W. Cao, L. Yang, F. F. Wang, and L. M. Tolbert, "Virtual synchronous generator control of full converter wind turbines with short-term energy storage," *IEEE Trans. Ind. Electron.*, vol. 64, no. 11, pp. 8821–8831, 2017.

[45] C. Andalib-Bin-Karim, X. Liang, and H. Zhang, "Fuzzy-secondary-controller-based virtual synchronous generator control scheme for interfacing inverters of renewable distributed generation in microgrids," *IEEE Trans. Ind. Appl.*, vol. 54, pp. 1047–1061, March 2018.

[46] M. F. Zia, E. Elbouchikhi, and M. Benbouzid, "Microgrids energy management systems: A critical review on methods, solutions, and prospects," *Appl. Energy*, vol. 222, pp. 1033–1055, 2018.

[47] M. Hemmati, B. Mohammadi-Ivatloo, M. Abapour, and A. Anvari-Moghaddam, "Optimal chance-constrained scheduling of reconfigurable microgrids considering islanding operation constraints," *IEEE Syst. J.*, vol. 14, no. 4, pp. 5340–5349, 2020.

[48] M. Mohiti, H. Monsef, A. Anvari-Moghaddam, and H. Lesani, "Two-stage robust optimization for resilient operation of microgrids considering hierarchical frequency control structure," *IEEE Trans. Ind. Electron.*, vol. 67, no. 11, pp. 9439–9449, 2019.

[49] B. Zhao, X. Wang, D. Lin, M. M. Calvin, J. C. Morgan, R. Qin, and C. Wang, "Energy management of multiple microgrids based on a system of systems architecture," *IEEE Trans. Power Syst.*, vol. 33, pp. 6410–6421, Nov 2018.

[50] H. Alharbi and K. Bhattacharya, "Stochastic optimal planning of battery energy storage systems for isolated microgrids," *IEEE Trans. Sustain. Energy*, vol. 9, pp. 211–227, Jan 2018.

[51] S. Esmaeili, A. Anvari-Moghaddam, and S. Jadid, "Optimal operation scheduling of a microgrid incorporating battery swapping stations," *IEEE Trans. Power Syst.*, vol. 34, no. 6, pp. 5063–5072, 2019.

[52] Y. Mi, H. Zhang, Y. Fu, C. Wang, P. C. Loh, and P. Wang, "Intelligent power sharing of dc isolated microgrid based on fuzzy sliding mode droop control," *IEEE Trans. Smart Grid*, vol. 10, pp. 2396–2406, May 2019.

[53] L. Meng, E. R. Sanseverino, A. Luna, T. Dragicevic, J. C. Vasquez, and J. M. Guerrero, "Microgrid supervisory controllers and energy management systems: A literature review," *Renewable Sustain. Energy Rev.*, vol. 60, pp. 1263–1273, 2016.

[54] D. Arcos-Aviles, F. Guinjoan, J. Pascual, L. Marroyo, P. Sanchis, R. Gordillo, P. Ayala, and M. P. Marietta, "A review of fuzzy-based residential grid-connected microgrid energy management strategies for grid power profile smoothing," in *Energy Sustain. in Built and Urban Environ.*, pp. 165–199, Springer, 2019.

[55] A. A. Anderson and S. Suryanarayanan, "A comprehensive review of energy management and planning of islanded microgrids: Part 1 — optimization formulations," *CSEE J. of Power and Energy Syst.*, pp. 1–15, 2019.

[56] M. Vahedipour-Dahraie, A. Anvari-Moghaddam, and J. M. Guerrero, "Evaluation of reliability in risk-constrained scheduling of autonomous microgrids with demand response and renewable resources," *IET Renewable Power Gener.*, vol. 12, no. 6, pp. 657–667, 2018.

[57] N. Bazmohammadi, A. Tahsiri, A. Anvari-Moghaddam, and J. M. Guerrero, "Stochastic predictive control of multi-microgrid systems," *IEEE Trans. Ind. Appl.*, vol. 55, no. 5, pp. 5311–5319, 2019.

[58] M. Parvania, M. Fotuhi-Firuzabad, and M. Shahidehpour, "Comparative hourly scheduling of centralized and distributed storage in day-ahead markets," *IEEE Trans. Sustain. Energy*, vol. 5, no. 3, pp. 729–737, 2014.

[59] D. Bertsimas, E. Litvinov, X. A. Sun, J. Zhao, and T. Zheng, "Adaptive robust optimization for the security constrained unit commitment problem," *IEEE Trans. Power Systems*, vol. 28, no. 1, pp. 52–63, 2013.

[60] R. Jiang, M. Zhang, G. Li, and Y. Guan, "Two-stage network constrained robust unit commitment problem," *European Journal of Operational Research*, vol. 234, no. 3, pp. 751–762, 2014.

[61] S. Leonori, A. Martino, F. M. F. Mascioli, and A. Rizzi, "Microgrid energy management systems design by computational intelligence techniques," *Applied Energy*, vol. 277, p. 115524, 2020.

[62] O. Boqtob, H. El Moussaoui, H. El Markhi, and T. Lamhamdi, "Optimal robust unit commitment of microgrid using hybrid particle swarm optimization with sine cosine acceleration coefficients," *Int. J. Renewable Energy Res. (IJRER)*, vol. 9, no. 3, pp. 1125–1134, 2019.

[63] R. Nivedha R, J. Govind Singh, and W. Ongsakul, "Pso based unit commitment of a hybrid microgrid system," in *2018 Int. Conf. Utility Exhib. Green Energy for Sustain. Dev. (ICUE)*, pp. 1–6, Oct 2018.

[64] G. Van den Broeck, J. Stuyts, and J. Driesen, "A critical review of power quality standards and definitions applied to dc microgrids," *Appl. Energy*, vol. 229, pp. 281–288, 2018.

[65] Y. K. Yeh, G. W. Chang, Y. J. Liu, T. K. Nguyen, Y. R. Chang, and Y. D. Lee, "A study on control strategy of pv inverter for harmonic mitigation in a microgrid," in *2018 IEEE PESGM*, pp. 1–5, Aug 2018.

[66] S. Yang, P. Wang, Y. Tang, and L. Zhang, "Explicit phase lead filter design in repetitive control for voltage harmonic mitigation of vsi-based islanded microgrids," *IEEE Trans. Ind. Electron.*, vol. 64, no. 1, pp. 817–826, 2017.

[67] N. Alwaz, S. Raza, S. Ali, M. K. L. Bhatti, and S. Zahra, "Harmonic power sharing and power quality improvement of droop controller based low voltage islanded microgrid," in *2019 Int. Symp. on Recent Advances in Elect. Eng. (RAEE)*, vol. 4, pp. 1–6, Aug 2019.

[68] M. S. K. Khadem, M. Basu, and M. F. Conlon, "Upqc for power quality improvement in dg integrated smart grid network-a review," *Int. J. Emerg. Elect. Power Syst.*, vol. 13, no. 1, 2012.

[69] S. Devassy and B. Singh, "Design and performance analysis of three-phase solar pv integrated upqc," *IEEE Trans. Ind. Appl.*, vol. 54, no. 1, pp. 73–81, 2017.

[70] S. Devassy and B. Singh, "Performance analysis of solar pv array and battery integrated unified power quality conditioner for microgrid systems," *IEEE Trans. Ind. Electron.*, 2020.

[71] S. Lakshmi and S. Ganguly, "An on-line operational optimization approach for open unified power quality conditioner for energy loss minimization of distribution networks," *IEEE Trans. Power Syst.*, vol. 34, no. 6, pp. 4784–4795, 2019.

[72] U. K. Renduchintala and C. Pang, "Neuro-fuzzy based upqc controller for power quality improvement in micro grid system," in *2016 IEEE/PES Transmiss. Distrib. Conf. Expo. (T&D)*, pp. 1–5, IEEE, 2016.

[73] Y. Zhong, M. Xia, and H.-D. Chiang, "Electric vehicle charging station microgrid providing unified power quality conditioner support to local power distribution networks," *Int. Trans. Elect. Energy Syst.*, vol. 27, no. 3, p. e2262, 2017.

[74] J. Alshehri and M. Khalid, "Power quality improvement in microgrids under critical disturbances using an intelligent decoupled control strategy based on battery energy storage system," *IEEE Access*, vol. 7, pp. 147314–147326, 2019.

[75] P. Wang, X. Lu, W. Wang, and D. Xu, "Frequency division based coordinated control of three-port converter interfaced hybrid energy

storage systems in autonomous dc microgrids," *IEEE Access*, vol. 6, pp. 25389–25398, 2018.

[76] T. Morstyn, B. Hredzak, and V. G. Agelidis, "Control strategies for microgrids with distributed energy storage systems: An overview," *IEEE Trans. Smart Grid*, vol. 9, pp. 3652–3666, July 2018.

[77] K. Knezović, S. Martinenas, P. B. Andersen, A. Zecchino, and M. Marinelli, "Enhancing the role of electric vehicles in the power grid: Field validation of multiple ancillary services," *IEEE Trans. on Transp. Electrific.*, vol. 3, pp. 201–209, March 2017.

[78] H. Liu, J. Qi, J. Wang, P. Li, C. Li, and H. Wei, "Ev dispatch control for supplementary frequency regulation considering the expectation of ev owners," *IEEE Trans. Smart Grid*, vol. 9, pp. 3763–3772, July 2018.

[79] A. Rabie, A. Ghanem, S. Kaddah, and M. El-Saadawi, "Frequency stability in weak grids using independent electric vehicle," in *2019 21st Int. Middle East Power Syst. Conf. (MEPCON)*, pp. 423–428, Dec 2019.

[80] M. Shafie-khah, M. Vahid-Ghavidel, M. Di Somma, G. Graditi, P. Siano, and J. P. S. Catalão, "Management of renewable-based multi-energy microgrids in the presence of electric vehicles," *IET Renewable Power Gener.*, vol. 14, no. 3, pp. 417–426, 2020.

[81] Y. R. Rodrigues, M. F. Z. de Souza, A. C. Z. de Souza, B. I. L. Lopes, and D. Q. Oliveira, "Unbalanced load flow for microgrids considering droop method," in *2016 IEEE PESGM*, pp. 1–5, July 2016.

[82] M. S. Ahmad and S. Sivasubramani, "Feasibility of v2g ideology in developing economy : Operation, analysis and impact," in *2016 Nat. Power Syst. Conf. (NPSC)*, pp. 1–5, Dec 2016.

[83] M. Fakhari Moghaddam Arani and Y. A. I. Mohamed, "Cooperative control of wind power generator and electric vehicles for microgrid primary frequency regulation," *IEEE Trans. Smart Grid*, vol. 9, pp. 5677–5686, Nov 2018.

[84] D. R. Nair, Devi S., M. G. Nair, and K. Ilango, "Tariff based fuzzy logic controller for active power sharing between microgrid to grid with improved power quality," in *2016 Int. Conf. Energy Efficient Technol. Sustain. (ICEETS)*, pp. 406–409, April 2016.

[85] A. Rabiee, H. Feshki Farahani, M. Khalili, J. Aghaei, and K. M. Muttaqi, "Integration of plug-in electric vehicles into microgrids as energy and reactive power providers in market environment," *IEEE Trans. Ind. Informat.*, vol. 12, pp. 1312–1320, Aug 2016.

[86] M. Farrokhabadi, S. König, C. A. Cañizares, K. Bhattacharya, and T. Leibfried, "Battery energy storage system models for microgrid stability analysis and dynamic simulation," *IEEE Trans. Power Syst.*, vol. 33, pp. 2301–2312, March 2018.

[87] S. Ahn, J. Park, I. Chung, S. Moon, S. Kang, and S. Nam, "Power-sharing method of multiple distributed generators considering control modes and configurations of a microgrid," *IEEE Trans. Power Del.*, vol. 25, no. 3, pp. 2007–2016, 2010.

[88] S. Kotra and M. K. Mishra, "Design and stability analysis of dc microgrid with hybrid energy storage system," *IEEE Trans. Sustain. Energy*, vol. 10, pp. 1603–1612, July 2019.

[89] G. Oriti, N. Anglani, and A. L. Julian, "Hybrid energy storage control in a remote military microgrid with improved supercapacitor utilization and sensitivity analysis," *IEEE Trans. Ind. Appl.*, vol. 55, pp. 5099–5108, Sep. 2019.

[90] S. Kotra and M. K. Mishra, "Design and stability analysis of dc microgrid with hybrid energy storage system," *IEEE Trans. Sustain. Energy*, vol. 10, no. 3, pp. 1603–1612, 2019.

[91] F. Alkarrami, T. Iqbal, and K. Pope, "Optimal sizing of a stand-alone hybrid energy system for water pumping in sirte, libya," in *2016 IEEE Elect. Power and Energy Conf. (EPEC)*, pp. 1–5, Oct 2016.

[92] A. Ahadi and X. Liang, "A stand-alone hybrid renewable energy system assessment using cost optimization method," in *2017 IEEE Int. Conf. Ind. Technol. (ICIT)*, pp. 376–381, March 2017.

[93] J. Liu, W. Zhang, and G. Rizzoni, "Robust stability analysis of dc microgrids with constant power loads," *IEEE Trans. Power Syst.*, vol. 33, pp. 851–860, Jan 2018.

[94] C. Wang, T. Zhang, F. Luo, F. Li, and Y. Liu, "Impacts of cyber system on microgrid operational reliability," *IEEE Trans. Smart Grid*, vol. 10, pp. 105–115, Jan 2019.

[95] R. Yokoyama, T. Niimura, and N. Saito, "Modeling and evaluation of supply reliability of microgrids including pv and wind power," in *2008 IEEE PESGM*, pp. 1–5, 2008.

[97] M. Al-Muhaini, A. Bizrah, G. Heydt, and M. Khalid, "Impact of wind speed modelling on the predictive reliability assessment of wind-based

[96] P. M. de Quevedo, J. Contreras, A. Mazza, G. Chicco, and R. Porumb, "Modeling and reliability assessment of microgrids including renewable distributed generation," in *2016 IEEE 16th Int. Conf. Environ. Elect. Eng. (EEEIC)*, pp. 1–6, 2016.
microgrids," *IET Renewable Power Gener.*, vol. 13, no. 15, pp. 2947–2956, 2019.

[98] M. Vahedipour-Dahraie, H. Rashidizadeh-Kermani, A. Anvari-Moghaddam, and J. M. Guerrero, "Stochastic risk-constrained scheduling of renewable-powered autonomous microgrids with demand response actions: Reliability and economic implications," *IEEE Trans. Ind. Appl.*, vol. 56, no. 2, pp. 1882–1895, 2020.

[99] S. Dinkhah, C. A. Negri, M. He, and S. B. Bayne, "V2g for reliable microgrid operations: Voltage/frequency regulation with virtual inertia emulation," in *2019 IEEE Transp. Electrific. Conf. Expo. (ITEC)*, pp. 1–6, IEEE, 2019.

[100] Y. Linhao, W. Ke, C. Xu, H. Tingcheng, and L. Mengying, "Reliability evaluation of microgrid considering electric vehicles and demand response," in *2018 Int. Conf. Power Syst. Technol. (POWERCON)*, pp. 1668–1672, 2018.

[101] X. Wang and R. Karki, "Exploiting phev to augment power system reliability," *IEEE Trans. Smart Grid*, vol. 8, no. 5, pp. 2100–2108, 2016.

[102] M. Zhang and J. Chen, "The energy management and optimized operation of electric vehicles based on microgrid," *IEEE Trans. Power Del.*, vol. 29, no. 3, pp. 1427–1435, 2014.

[103] H. Farzin, M. Moeini-Aghtaie, and M. Fotuhi-Firuzabad, "Reliability studies of distribution systems integrated with electric vehicles under battery-exchange mode," *IEEE Trans. Power Del.*, vol. 31, no. 6, pp. 2473–2482, 2015.

[104] M. Faisal, M. A. Hannan, P. J. Ker, A. Hussain, M. B. Mansor, and F. Blaabjerg, "Review of energy storage system technologies in microgrid applications: Issues and challenges," *IEEE Access*, vol. 6, pp. 35143–35164, 2018.

[105] W. Li *et al.*, *Reliability assessment of electric power systems using Monte Carlo methods*. Springer Science & Business Media, 2013.

[106] A. Muhtadi, D. Pandit, and N. Nguyen, "Renewable energy based microgrid: role of the architecture in grid enhancement towards sustainable energy," in *IEEE Ind. Appl. Society Annual Meeting*, 2020.

[107] L. Cheng, Y. Chang, J. Lin, and C. Singh, "Power system reliability assessment with electric vehicle integration using battery exchange mode," *IEEE Trans. Sustain. Energy*, vol. 4, no. 4, pp. 1034–1042, 2013.

[108] D. Wu, D. C. Aliprantis, and K. Gkritza, "Electric energy and power consumption by light-duty plug-in electric vehicles," *IEEE Trans. Power Syst.*, vol. 26, no. 2, pp. 738–746, 2011.

[109] "U.s. department of transportation, federal highway administration, 2017 national household travel survey." https://nhts.ornl.gov. Accessed: 2020-05-28.

[110] N. Nguyen, A. Bera, and J. Mitra, "Energy storage to improve reliability of wind integrated systems under frequency security constraint," *IEEE Trans. Ind. Appl.*, vol. 54, no. 5, pp. 4039–4047, 2018.

[111] C. Grigg, P. Wong, P. Albrecht, R. Allan, M. Bhavaraju, R. Billinton, Q. Chen, C. Fong, S. Haddad, S. Kuruganty, *et al.*, "The ieee reliability test system-1996. a report prepared by the reliability test system task force of the application of probability methods subcommittee," *IEEE Trans. Power Syst.*, vol. 14, no. 3, pp. 1010–1020, 1999.

[112] "Cooperative networks for renewable resource measurements solar energy resource data." https://www.nrel.gov/grid/solar-resource/confirm.html. Accessed: 2020-05-25.

[113] "Western wind dataset." NREL, Golden, CO (United States), 2015.

[114] N. Nguyen, A. Bera, and J. Mitra, "Energy storage to improve reliability of wind integrated systems under frequency security constraint," *IEEE Trans. Ind. Appl.*, vol. 54, no. 5, pp. 4039–4047, 2018.

[115] J. Choi, J. Park, M. Shahidehpour, and R. Billinton, "Assessment of co 2 reduction by renewable energy generators," in *2010 Innov. Smart Grid Technol. (ISGT)*, pp. 1–5, IEEE, 2010.

[116] P. Giorsetto and K. F. Utsurogi, "Development of a new procedure for reliability modeling of wind turbine generators," *IEEE Trans. Power App. and Syst.*, vol. PAS-102, no. 1, pp. 134–143, 1983.

[117] C. Singh, P. Jirutitijaroen, and J. Mitra, *Electric Power Grid Reliability Evaluation: Models and Methods*. John Wiley & Sons, 2018.